DEVELOPMENT OF FLIGHT TECHNOLOGY FOR FUTURE LASER-COOLED SPACE CLOCKS

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In this paper we report on the development of flight technologies to be used in space-based, laser-cooled atomic clocks scheduled to fly on the International Space Station. The core technologies for these and future Laser Cooling and Atomic Physics (LCAP) missions are being developed in the Time and Frequency Sciences and Technology group at the Jet Propulsion Laboratory. We are currently focussing on high-risk components such as the laser and optics subsystem and mechanical shutters to provide light baffling while allowing quasi-continuous atomic beams through the clock.

The outstanding performance of laser-cooled atomic fountain clocks on the ground and the promise of improved performance in space leave us with the task of repackaging fountain technologies for flight. This involves increasing the ruggedness and reliability in order to withstand typical launch conditions and achieve several months of unattended operation. Microgravity clocks will operate differently from their Earth-bound counterparts, requiring development of special capabilities, including the above-mentioned shutters and the use of special materials and designs as discussed briefly below.

Both PARCS[1] and RACE[2] are planned to fly for one year missions aboard the International Space Station (ISS). They will be located on the Japanese Experiment Modules Exposed Facility (JEM-EF), shown in Fig. 1. On the JEM-EF instruments mount into a volume of 1.8x 1.0x 0.8 m and allow masses up to 500 kg. JEM-EF sites have cooling loops capable of carrying away 2000 W of heat. The generous payload accommodations are further complemented by the ability to locate the clock instruments immediately next to GPS antennae to be used for orbit determination and frequency transfer. A conceptual configuration for the RACE instrument appears in Fig. 2, showing

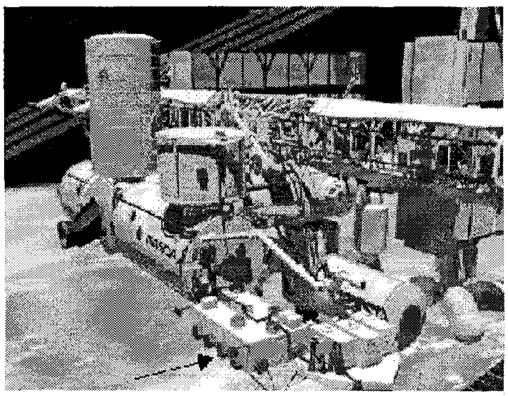

Figure 1 The arrow points to an attachment point on the Japanese Experiment Module Exposed Facility (JEM-EF).

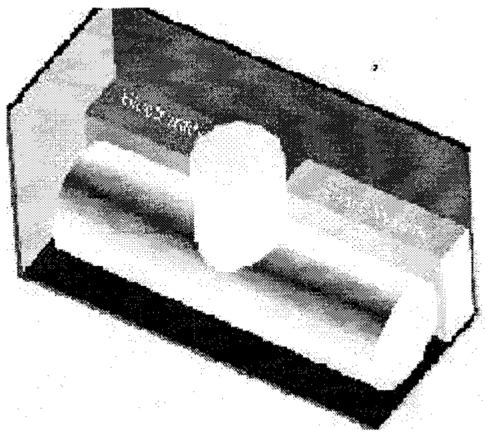

Figure 2 Possible configuration for the RACE instrument within the envelope allowed on the JEM-EF.

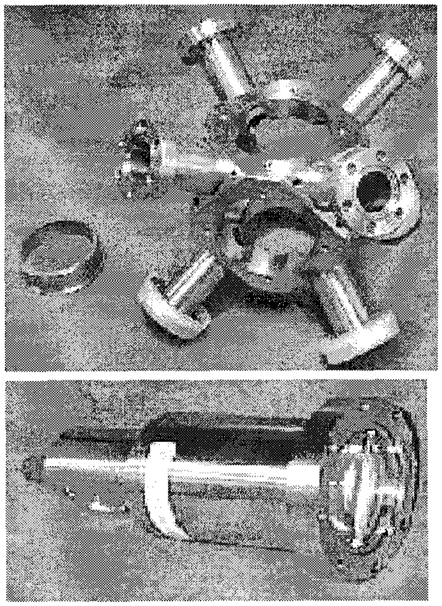

Figure 3 Titanium atom collection chamber with weldable window (top). Fiber-coupled collimator in compact package with power-monitoring port (bottom).

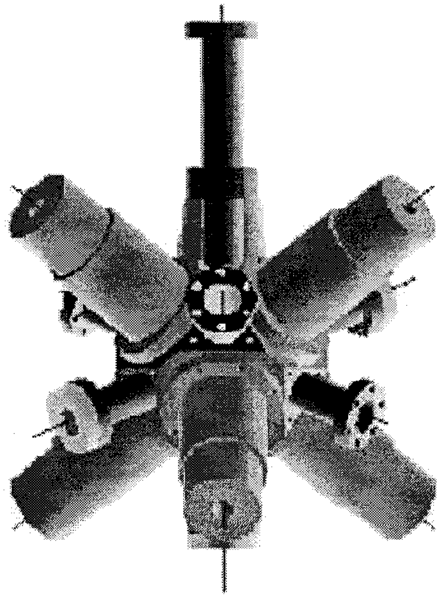

Figure 4 CAD drawing showing collection chamber with collimators attached.

the outer shield of the physics package, and envelopes for the electronics package and laser and optics assembly.

The most obvious difference between a microgravity clock and its Earth-bound counterpart is that atoms in the microgravity clock travel with constant speed, while in a fountain they accelerate strongly under the pull of gravity. This allows for longer interrogation times but comes with some design consequences as well. In a typical fountain the distance between the atom-collection region and the Ramsey interrogation region is 0.5 meters, with that distance covered in 150 ms. Generous clearance exists for adding short sections into the fountain and the short time of flight to the Ramsey region eliminates the need for great economy on this distance. In the microgravity clocks, the longest linear dimension is strictly bounded, and with atoms moving at constant speeds of 5-10 cm/s that same 0.5 meters would require 5-10 seconds of drift time, resulting in a significant reduction in performance. This drives a design which minimizes the distance between atom collection and microwave cavities and distance to the detection region. This suggests locating the entire physics package inside the magnetic shields, driving the use of non-magnetic materials, and sets additional constraints on the vacuum requirements in the source region in particular.

Fig. 3 shows the titanium atom-collection chamber designed to provide large optical access in a compact design. The chamber is made of titanium, chosen for its vacuum and magnetic properties and also its light weight. Also shown are the custom windows which provide 3.8 cm clear aperature in a titanium weld sleeve. The windows are re-entrant into the chamber, minimizing

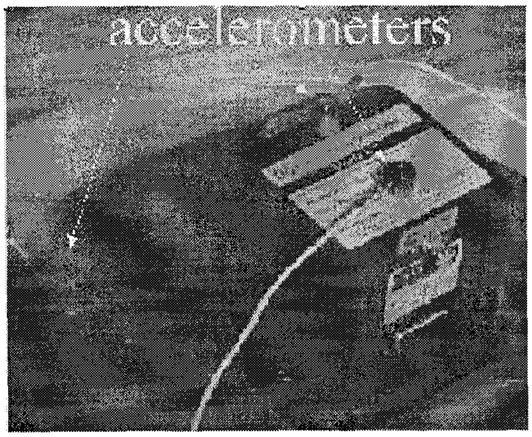

Figure 5 New Focus Vortex Laser on a shake-table at JPL.

space and allowing the optical collimators to be bolted directly to the collection chamber. The collimators also utilize a custom design to reduce their length by a factor of three over a single-lens design. The housing is also made of titanium and uses all non-magnetic parts in the assembly. Fig. 4 shows a CAD drawing of the chamber with the six collimators bolted on.

In order to minimize the cost of these missions, we plan to rely on commercial off-the-shelf (COTS) components where possible. Since the mission performance depends so critically on the performance of the lasers and optics we have subjected commercial components commonly used in ground laboratories to vibrational levels consistent with launching on the Space Shuttle. Fig. 5 shows an external cavity laser on the shake table with monitoring accelerometers. We tested the components we felt most likely to break during launch, including the laser, acousto-optic modulators, and optical isolators. All passed with no damage.

Certain key components of these missions are not available commercially and must be developed. In order to realize the highest stability while minimizing the cold-collision frequency shift both PARCS and RACE will run a quasi-continuous stream of atoms through the microwave cavities by launching multiple balls of atoms in rapid succession. To avoid light shifts from the laser light, shutters are needed inside the vacuum system to allow atoms to pass but to baffle the light. These shutters must operate in a vacuum, be non-magnetic, open greater than 1 cm, have a long lifetime, be compatible with our ultra-high vacuum environment and produce a minimum of vibration. We have developed a prototype shutter, shown in Fig. 6 and performed preliminary testing to demonstrate the success of our approach. The shutter arms are PZT driven and rely on a two-stage flexure amplification to realize the large aperture. Lifetime testing is currently underway.

One of the great challenges in these missions is developing precise optical alignments which are stable over the one

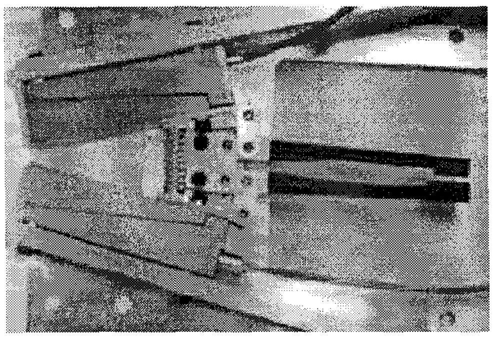

Figure 6 Prototype shutter to provide light baffling during quasi-continuous operation of the clock.

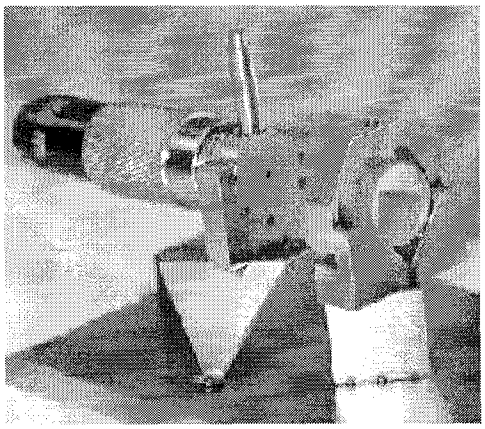

Figure 7 An optical fiber and collimating lens in mounts positioned and then fixed using a laser welder.

year lifetime of these missions under a fairly wide range of temperature. Techniques for maintaining alignments over long times and under changes in temperature are being developed using a laser welder. 6-axis positioning is accomplished by mounting optics on tripod bases which are then laser-welded to a base plate, as shown in Fig. 7. An assembly for testing fiber coupling is under construction and will be tested for mechanical and thermal stability.

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[1] PARCS, the Primary Atomic Reference Clock in Space, has Principle Investigator Don Sullivan at the National Institute of Standards and Technology and Neil Ashby from the University of Colorado. A summary of the experimental objectives can be found in S.R. Jefferts, et al., "PARCS: a Primary Atomic Reference Clock in Space," Proceedings of the 1999 Joint Meeting of the European Frequency and Time Forum and the IEEE International Frequency Control Symposium, p. 141-4.

[2] RACE, the Rubidium Atomic Clock Experiment, is led by Principle Investigator Kurt Gibble at Yale University. A paper describing RACE appears in these Proceedings.